

Practical scheme for fibre-optical QKD with polarization encoded qubits using real-time polarization control

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Abstract

We present a practical scheme for a quantum key distribution system via optical fibers employing polarization-encoded qubits with real-time polarization control. Alice sends faint laser pulses along with classical control channels via a WDM, which are used by Bob to apply a unitary transformation that cancels out the polarization rotations induced by the time-varying birefringence in the quantum channel. It is experimentally shown that the system is very robust against severe polarization fluctuations in the optical fiber, such as those found in aerial cables under strong wind conditions, thus providing high stability for continuous operation at fast bit rates.

Introduction

The polarization state of the photon is a natural degree of freedom to encode qubits, thanks to the ease to manipulate it experimentally. Today's most, if not all, free space Quantum Key Distribution (QKD) demonstrations use polarization coding. Whereas the atmospheric channel shows negligible anisotropy, the same is not true for fibre-optical links, which show residual time-varying birefringence [1]; as such, the polarization state of a single photon sent by Alice is randomly changed along its propagation towards Bob, which means that the received qubits may bear no correlation whatsoever to the original states. For this reason, polarization coding is unpractical for fibre-optical quantum communications, unless an active polarization control system is used. Moreover, in future quantum networks exploiting Bell state measurements, the control of the polarization state will be necessary.

We propose a practical setup for fibre-optical QKD using polarization encoding. In order for the system to be able to operate continuously, the polarization control must be completely transparent to the quantum layer. This can be achieved if two fixed wavelength-multiplexed non-orthogonal polarization states are sent by Alice as reference signals along with the qubits [2]. Depending on the behaviour of the reference signals, Bob can infer the unitary transformation that has been introduced by the fibre and apply its inverse to restore the original polarization state of the photon.

Experimental setup

Figure 1 shows the proposed setup for the QKD system. Alice prepares her qubits by pulsing a laser

diode (LD) operating at $\lambda_Q = 1546.12$ nm with a 5MHz pulse rate and randomly selecting with an electro-optic LiNbO₃ polarization controller (PC) one out of four possible polarization states along the equator of the Poincaré sphere. An attenuator (A) reduces signal intensity to the single-photon level. A coupler (C) combines the quantum channel with two reference signals, generated by independent laser diodes at wavelengths $\lambda_1 = 1545.32$ nm and $\lambda_3 = 1546.92$ nm, which have their polarization states manually adjusted as horizontal and +45° respectively.

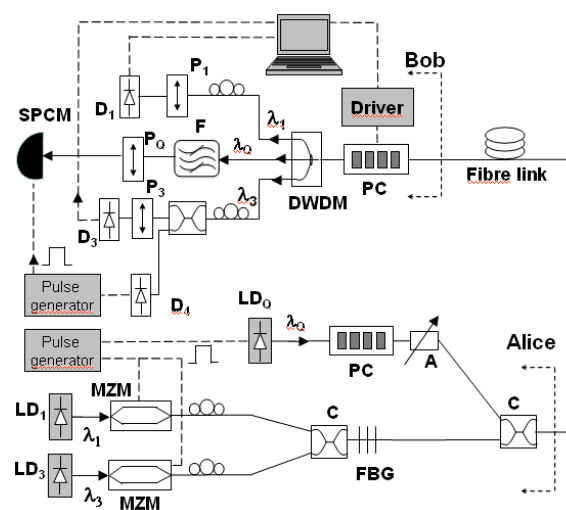


Figure 1: Experimental setup. See text for details.

A fibre Bragg grating (FBG) with maximum reflectivity at the quantum channel's wavelength is used to avoid additional noise; moreover, the same pulse generator that drives the quantum channel's laser also drives two Mach-Zehnder Modulators (MZM) in front of each side channel laser, in order to ensure that no

reference signals are sent in a time window that includes the duration of the qubit. This is necessary because, otherwise, the noise count rate would be orders of magnitude higher due to Raman scattering [3]. As the duration of the window is around 20 ns, these interruptions are not noticed by the detectors responsible for the polarization control (D1, D3), thus ensuring the transparency of the control system. On the other hand, a fast detector (D4) is used to detect these pulses for clock recovery, thus eliminating the need for additional synchronisation signals.

After propagation in the optical fibre link, Bob uses a Dense Wavelength Division Multiplexer (DWDM) with >50dB rejection between adjacent channels to separate the reference signals from the qubits and perform the polarization control via a closed-loop configuration [2]. A polarization controller (PC) similar to Alice's is used both to apply the unitary transformation to recover the original polarization states of the qubits as well as to perform a random active choice of basis for detection by a single photon counting module (SPCM), after passage through a filter (F) with an additional >50 dB rejection and a polarizer (P), which should be replaced by a polarizing beam splitter if an additional SPCM is available.

Experimental results

The performance of our setup depends on three conditions: (1) the efficiency and stability of the polarization control system, (2) the bandwidth modulation of the polarization state of the single photons (> 5 MHz) and (3) the additional noise at Bob's SPCM due to the reference signals.

The stability and efficiency of the control system, was verified by replacing the SPCM with a polarimeter. Figure 2 shows a histogram of the fidelity between the original states sent by Alice and the received states detected by Bob over 90 minutes of measurement for a transmission via a flexible optical fibre cable suspended in the top of a seven-story building, subjected to oscillations caused by the wind.

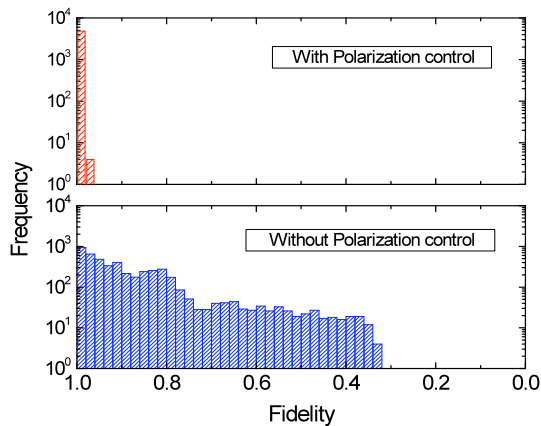


Figure 2: Fidelity between the polarization states sent by Alice and received by Bob.

It is clear from the measurement that the control system is absolutely necessary for a successful key exchange under fluctuations of that level. The response time of the polarization control system is ~1ms, thus allowing correction for fast polarization fluctuations, such as those found in an aerial cable. It should be noticed, however, that the PMD of the fibre must be low enough for correct operation [4].

The ability of our system to send qubits at a 5 MHz rate is shown in figure 3, which depicts a sample pulse corresponding to a transition between two orthogonal states for a fixed basis. As the measured rise/fall time is around 10ns, limited by our pulse generator, data rates higher than 50 Mbps could, in principle, be achieved.

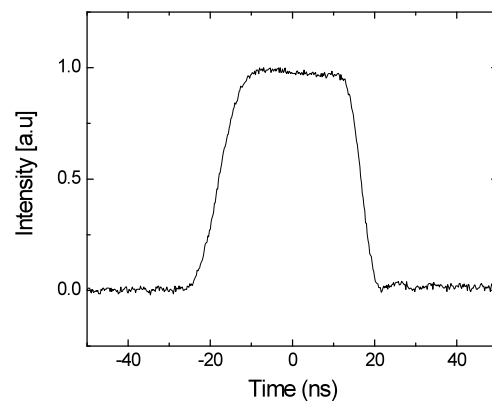


Figure 3: Transmitted intensity through Bob's polarizer corresponding to a 010 sequence from Alice.

Finally, the noise count rate at Bob's SPCM was measured in the single-photon counting level with Alice's quantum channel laser turned off. For a detection gate of 2.5 ns and a gating frequency of 5 MHz, the measured probability of noise was 3×10^{-6} , which is smaller than the SPCM's dark count probability of approx. 10^{-5} per gate.

Conclusions

A practical scheme for fibre-optical QKD with polarization encoding using real-time polarization control was presented. Fast control was demonstrated and repetition rates up to 50 Mbps can be achieved with continuous stable operation. Negligible noise is added to the quantum channel by the control signals.

References

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